



## Search for Ultra-High Energy Photons with the Pierre Auger Observatory

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**Abstract:** Data taken at the Pierre Auger Observatory are used to search for air showers initiated by ultra-high energy (UHE) photons. Results of searches are reported from hybrid observations where events are measured with both fluorescence and array detectors. Additionally, a more stringent test of the photon fluxes predicted with energies above  $10^{19}$  eV is made using a larger data set measured using only the surface detectors of the observatory.

### Introduction

It has been suggested that the excess of cosmic-rays with energies above the predicted Greisen-Zatsepin-Kusmin (GZK) steepening, observed by AGASA, could be due to cosmic-rays being produced as the by-products of 'top-down' scenarios and not by more conventional acceleration mechanisms, such as the diffusive shock process, in astrophysical objects. If the former were the case, it would be expected that a significant proportion of the spectrum of cosmic rays at the highest energies would be UHE photons: predictions vary from model to model but are in the range 10% to 50% above  $10^{19}$  EeV. The extensive air showers (EAS) generated by UHE photons reach shower maximum  $X_{\max}$ , the atmospheric depth at which the number of charged particles in the shower is greatest, at much greater depths than their nuclear counterparts. This is due to the much lower multiplicity in particle production in the electromagnetic-dominated photon showers than in the hadronic interactions present for nuclear primaries. The depth of maximum is further increased above  $30^{19}$  EeV because of the suppression of Bethe-Heitler pair production due to the LPM effect [5][6], which is not important for other cosmic-ray primaries.

$X_{\max}$  can thus be used to discriminate between photon and nucleonic UHE primaries. With

the Pierre Auger Observatory this can be done using hybrid events which are observed with both fluorescence and array detectors, and in which  $X_{\max}$  is measured directly. This allows the determination of a limit to the integral fraction of photons above  $10^{19}$  EeV. Parameters measured using only the surface array of detectors, which reflect shower maximum, can also be compared to predictions for photons from simulations to provide a stronger limit on the flux of photons at several energies [1]. Two such observables are used which behave differently for nuclear primaries when compared to photons: these are the risetime of the signal in the water-Cherenkov detectors at 1000 m from the core and the radius of curvature of the shower front.

### Analysis of Array Measurements

Data were taken with the surface detector over the period 1 January 2004 to 31 December 2006 for showers with zenith angles of  $30^\circ$  to  $60^\circ$ , corresponding to an aperture of  $3130 \text{ km}^2 \text{ sr yr}$ . For each event, the risetime at 1000 m,  $t_{1/2}(1000)$ , and the radius of curvature  $R_c$  was found. Photon candidates were selected with a cut determined *a priori* with the characteristics that these parameters were expected to display if they were photonic, de-

rived using Monte Carlo simulations. Upper limits were then calculated, both to the absolute flux and to the fraction of photons from the number of photon candidates. The motivation for using the chosen parameters is now discussed.

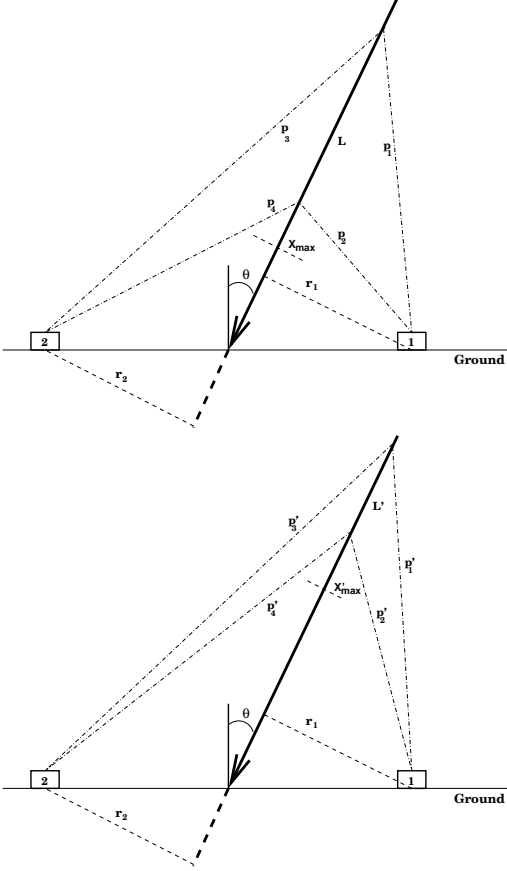


Figure 1: Example of the difference in path lengths for particles arriving at detectors of an EAS with different  $X_{\max}$ . The top drawing shows a deeply penetrating shower while on the bottom is a shallow shower ( $X_{\max} > X'_{\max}$ ). The difference in paths is larger for the deeper shower resulting in greater time spreads. Although  $r_1 = r_2$ , station 2 samples the shower later in the development than station 1 introducing an asymmetry in the measurement of  $t_{1/2}$ .

## Risetime

The arrival time distribution of particles in showers is expected to become more dispersed with increasing  $X_{\max}$  due to the geometry associated with particles in the shower: the difference in path lengths between particles produced early and late in the shower is greater for EAS which penetrate deeper into the atmosphere as demonstrated in figure 1. Photon showers dissipate energy over larger atmospheric track lengths than their nuclear counterparts, reaching  $X_{\max}$  deeper in the atmosphere and increasing the spread of the time signals relative to hadronic primaries.

The signal time spreads are evaluated by defining the risetime,  $t_{1/2}$ , as the time it takes for the signal to rise from 10% to 50% of the total signal deposited in the array detectors. Each measurement of  $t_{1/2}$  is corrected for asymmetry effects: stations which lie at similar core distances in the same event will sample the shower at different stages of development, due to the different azimuthal directions of the stations relative to the shower plane. This is demonstrated in figure 1, where station 2 samples the shower later in the development than station 1, resulting in a shorter signal despite the core distances being identical.

On an event-by-event basis, the estimated risetime at 1000 m from the core,  $t_{1/2}(1000)$  is found by fitting the risetimes from individual stations as a function of core distance. Due to the much larger  $X_{\max}$  expected from photons than nuclei, one would expect larger  $t_{1/2}(1000)$  for photons than from proton or iron primaries.

## Radius of Curvature

The early stages of a shower include the production of high energy muons which are relatively unscattered as they propagate to the ground. Accordingly they form a shower front which expands in an approximately spherical manner, where the radius of curvature of this sphere,  $R_c$ , is related to the distance of the observer from the production region of the muons, which in turn relates to  $X_{\max}$ . One

would thus expect larger values of  $X_{\max}$  to be reflected by smaller values of  $R_c$ .

## Results and Discussion

### Hybrid Results

In [3] we reported a limit to the fraction of photons in the integral cosmic-ray flux of 16% (95% c.l.) above 10 EeV based on 29 high-quality hybrid events recorded in the period Jan. 2004 - Feb. 2006. We have updated the analysis with data collected until March 2007, keeping the analysis cuts as in the original paper. In total, 58 events are now available. The measured  $X_{\max}$  distribution is shown in figure 2 along with the calculated distribution from 10 EeV photons made on an event-by-event basis. Even the largest observed value of  $X_{\max}$ ,  $\sim 900 \text{ g cm}^{-2}$ , is well below the average value expected for photons (about  $\sim 1000 \text{ g cm}^{-2}$ , see e.g. Table 1 in [3]). With the updated sample, the upper limit becomes 13% (95% c.l.) above 10 EeV.

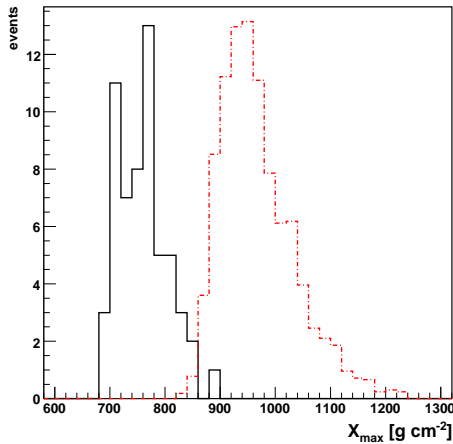


Figure 2: Black: The distribution of  $X_{\max}$  from 58 hybrid events with energies above 10 EeV that meet selected cuts[3]. The dashed line shows a distribution for 10 EeV photons arriving over a range of zenith angles. All events reach shower maximum at depths which are too shallow to be considered as a result of photon primaries.

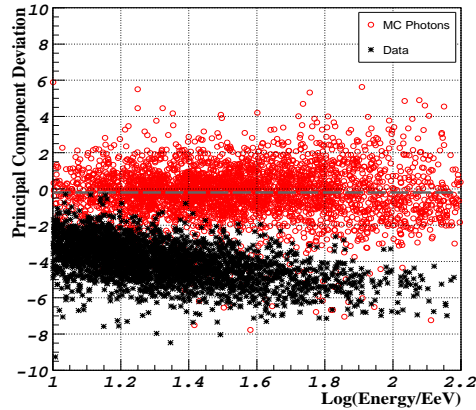


Figure 3: The principle component between risetime and radius of curvature as a function of energy for data (black) and simulated photons (red). Data lying above the dashed line, which is the mean of the distribution for photons, are identified as photon candidates. No events meet this requirement.

### Surface Detector Results

Photon candidates were searched for by combining the risetime and radius of curvature for each event into one observable using a principle component analysis, where the angle of rotation is found using 5% of the data. The remaining 95% of showers were then identified as nuclei or photon candidates using an *a priori* cut, where showers are excluded as photon-like if the principle component measurement is less than the mean of that predicted by a spectrum of photonic showers generated by Monte Carlo simulations. Events which were deemed as photonic were assigned energies using a reconstruction designed from photon simulations, reflecting the fact that these showers have low muon content and are more strongly attenuated than hadronic showers [2]. The spectrum of simulated photons incorporates the efficiency of photon detection and reconstructions, as well as including the possibility that photons may interact with the geomagnetic field before arriving in the atmosphere.

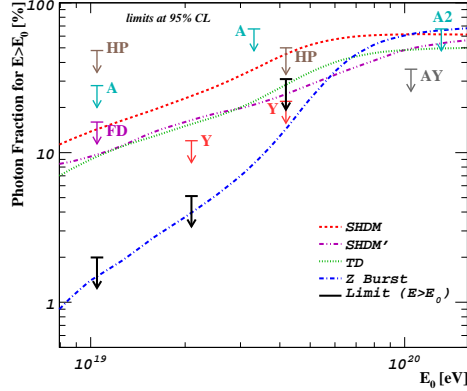
The results are summarised in figure 3 where the principle component is plotted for data (black) and the simulated photons (red) as a function of energy. There are 0 events above the dashed line, where the cut is defined, and as such there are no candidate photons for events above 10 EeV. This constrains the maximum flux of photons to  $3.8 \times 10^{-3}$ ,  $2.5 \times 10^{-3}$  and  $2.2 \times 10^{-3} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$  above 10, 20 and 40 EeV respectively.

The upper limit on the photon fraction, based on the measured spectrum of events in [4], is calculated as 2.0%, 5.1% and 31% at 10, 20 and 40 EeV respectively. These limits are shown against the predictions for photons from top-down models based on the AGASA spectrum (see [7]) in figure 4. Also shown are upper limits to the flux and fractions of photons from previous experiments. This work constrains the photon fractions and fluxes to more stringent limits than previously measured and disfavors the proposed top-down models as the sources of UHECRs and of the AGASA events.

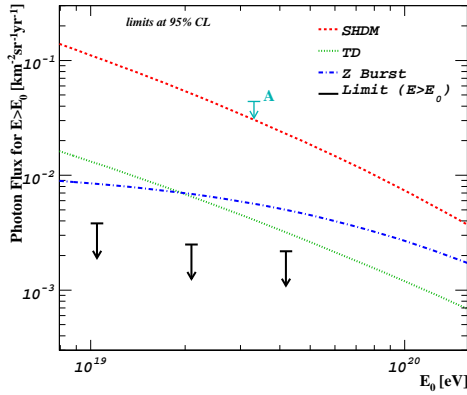
On completion of the surface array, the Pierre Auger Observatory will reach sensitivities of  $4 \times 10^{-4} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$  for the integrated flux and 0.7% for the fraction of photons above 20 EeV (95% c.l.) after 5 years of operation.

## References

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(a) Upper limits to photon fractions



(b) Upper limits to photon flux

Figure 4: (a) The upper limits to the fraction of photons including limits from previous experiments and predictions from top-down models based on the AGASA spectrum. The limits from this work are shown in black. The limit derived from the hybrid data is also shown and labelled FD. Labels A, HP and Y refer to the limits set by AGASA, Haverah Park and Yakutsk, for references see [7]. (b) The upper limits to the flux of photons along with predictions of top-down models.